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Vanguard/PLACE Experiment System Design and Test Plan

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Summary.—A system design and test plan are described for operational evaluation of the NASA-Goddard Position Location and Aircraft Communications Equipment (PLACE), at C-band (4/6GHz), using NASA's ship, the USNS Vanguard, and the ATS-3 and ATS-5 synchronous satellites. The Sea Test phase, extending from March 29, 1973 to April 15, 1973 has been successfully completed; the principal objectives of the experiment were achieved. Typical PLACE-computed, position-location data is shown for the Vanguard.

Position location and voice-quality measurements were excellent; ship position was determined within 2 nmi; high-quality, 2-way voice transmissions resulted as determined from audience participation, intelligibility and articulation-index analysis.

A C-band/L-band satellite trilateration experiment is discussed.

Introduction.—The Position Location and Aircraft Communications Equipment (PLACE) was designed for NASA's Applications Technology Satellite F (ATS-F). The basic purpose of the NASA-PLACE experiment is to obtain statistical information, engineering data, and practical experience for determining the operational utility and technical limitations of an oceanic Air Traffic Control (ATC) satellite system, operating at the aeronautical L-band frequencies (1540-1660 MHz).

This paper describes the system design and experiment test plan for testing the NASA-PLACE system at C-band using NASA's ship, the USNS Vanguard (Fig. 1) and the ATS-3 and ATS-5 satellites now in synchronous orbit. This test, known as the Vanguard/PLACE Experiment¹, was designed to give a preliminary evaluation of the PLACE concept one year in advance of ATS-F, scheduled for launch in early 1974.

Although the Vanguard sailed primarily to support the NASA Pioneer G(11) and Skylab missions, nevertheless, the northerly to southerly route of the Vanguard, from its berth at Port Canaveral, Florida to Mar del Plata, Argentina, provided an excellent opportunity to test the PLACE concept in a maritime environment. Furthermore, the availability of a C-band capability both onboard the Vanguard and at the NASA Space Flight and Data Network (STDN) station located at Rosman, North Carolina, provided a convenient tool to evaluate PLACE especially when combined with the C-band capability available on the ATS-3 and ATS-5 satellites.

The Maritime Administration (MARAD), U.S. Department of Commerce, as a co-experimenter² on the Vanguard, supplied the 2.5 ft-diameter, C-band, dish antenna system on the Vanguard, which included a C-band receiver (Fig. 1).

The 21 ft-diameter, ATS Mobile Terminal C-band antenna was already available at the Rosman station, similarly the 30 ft-diameter SATCOM, C-band antenna system was available on the Vanguard. Since ATS-5's high-gain, C-band antenna causes large pulsations in earth-received signals due to satellite spin, a crucial factor was the realization that the Vanguard's SATCOM antenna, and the ATS Mobile Terminal antenna, had sufficiently high effective-radiated-power (ERP) to employ the ATS-5 satellite's low-gain omnidirectional, C-band antenna (both transmit and receive). This made possible a complete PLACE experiment including ship position fixing, 2-way voice and 2-way data communications.

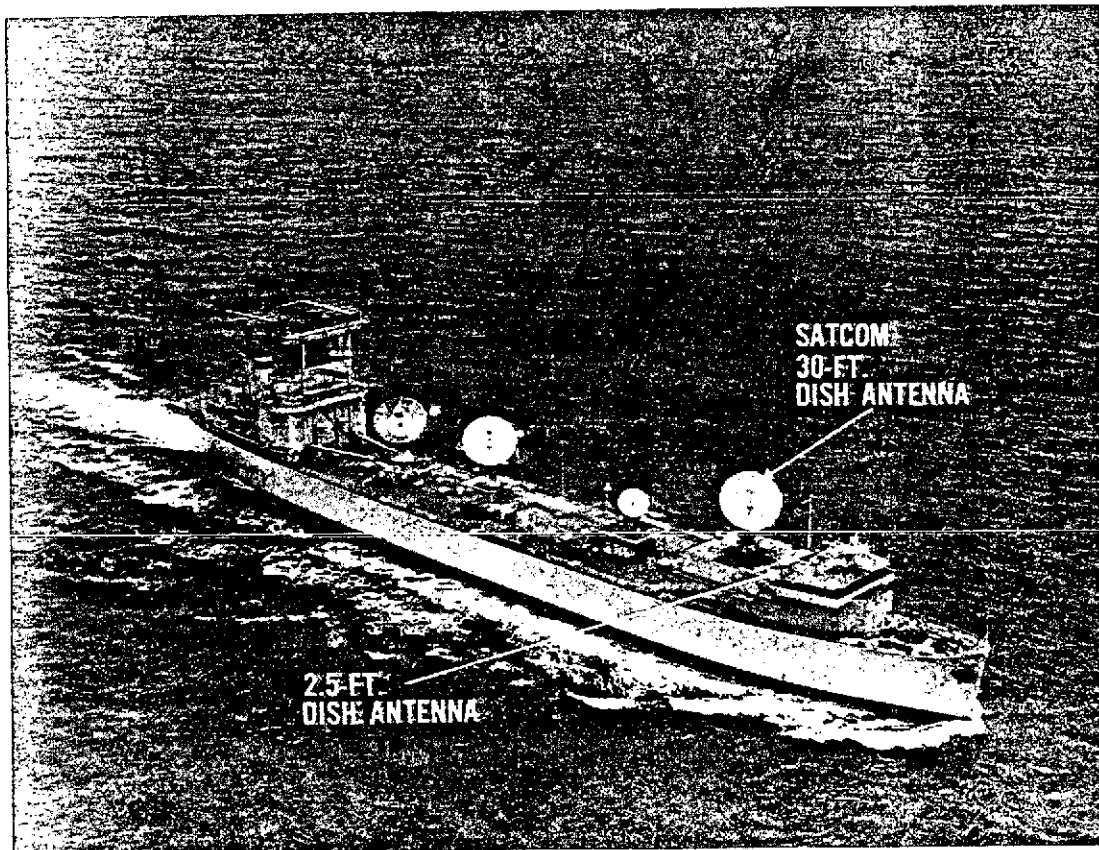


Fig. 1. NASA Ship, USNS Vanguard, Showing C-Band Antennas for PLACE Experiment

Operation at C-band (4/6 GHz) results in rf links that are essentially free of propagation anomalies caused by the ionosphere including propagation delay,³ Faraday rotation and scintillation, thereby providing an excellent test bed for PLACE system hardware. Since a slowly-moving ship does not simulate the Doppler and multipath environment experienced by a high-speed aircraft, the complete evaluation of the PLACE concept must await the launch of ATS-F when L-band links will be used.

The first documentation about the PLACE system originated from NASA-Goddard in 1967⁴ which was later updated in 1972.⁵ The ATS-F PLACE Experiment has been mentioned in the literature.⁶⁻⁸ Its primary function is to provide simultaneous surveillance and position fixing (within ± 1 nmi) for up to 250 aircraft, in addition to providing 2-way voice communications and 2-way, digital-data communications between a ground station and participating aircraft.

The position fixing of each mobile user (e.g., aircraft or ship) is determined directly from sidetone-ranging measurements between a ground station and each user, simultaneously through two synchronous satellites (e.g., ATS-3 and ATS-5).

An additional facet of the Vanguard/PLACE Experiment is to position-fix the location of the ATS-5 synchronous satellite with a triad of fixed ground stations including NASA's STDN stations located at Rosman, North Carolina; Mojave, California; and Mar del Plata, Argentina (Vanguard ship).

This portion of the experiment, known as the ATS-5 Trilateration Tests, is a demonstration of the capability of the PLACE system to position-fix the exact location of a synchronous satellite. In general, the ATS satellites are not in perfect geostationary orbits, but rather trace out either ellipses or figure eights over the earth.

Since the range from the Rosman station to each of the two ATS satellites is required as a priori information, these two ranges are provided either by satellite ephemeris data, or from a direct, in situ, measurement as performed by the trilateration tests.

The system design, and a test plan are described which include both Sea Tests and the ATS-5 Trilateration Tests. Following this, a preliminary test result is given for the position-location portion of the experiment.

Vanguard/PLACE Experiment. -The principal functions of the Vanguard/PLACE Experiment are as follows:

1. Real-time position fixing of ship, within ± 1 nmi, by 2-way, sidetone-ranging measurements simultaneously through two synchronous satellites (ATS-3 and ATS-5).
2. Duplex, 2-way, voice communications (shore-to-ship and ship-to-shore).
3. Duplex, 2-way, digital-data communications.
4. Data and voice (audio) multiple access.
5. Trilateration Tests to accurately position-fix ATS-5 satellite.

The principal objectives of the Vanguard/PLACE Experiment are:

1. Determination of position-fixing capability for a mobile user (Vanguard ship) compared to on board, precision, navigation instrumentation accurate within ± 0.1 nmi.
2. Demonstration of duplex-voice and duplex-data communications, and multiple accessing capability.
3. Demonstration of PLACE system in a maritime environment, of interest to the U.S. Department of Commerce, Maritime Administration (MARAD).
4. Demonstration of PLACE trilateration capability for position fixing a synchronous satellite (ATS-5).

The Vanguard/PLACE Experiment was divided into two phases: (1) a Sea Test during the Vanguard's voyage from March 28, 1973 until the following April 17th (20 days duration), and (2) ATS-5 Trilateration Tests starting May 3, 1973 for about two months. A pacing factor in the experiment schedule was the Vanguard's March 28th sailing date.

In order to obtain an independent position-fix for a mobile user (e.g., aircraft or ship), three ranging measurements are required: First, the range from satellite 1 (ATS-5) to the mobile user, R_1 ; second, the range from satellite 2 (ATS-3) to the same mobile user, R_2 ; and third, the range from the earth's geocenter to the mobile user, R_3 (Fig. 2). In the Vanguard/PLACE Experiment R_1 and R_2 are computed directly from sidetone-ranging measurements made by the PLACE ground station at Rosman, N.C.; whereas the location of the geocenter is known a priori. The user's height, h , is assumed as the mean sea level for the ship - in the case of an aircraft, h is measured with an onboard altimeter and telemetered back to the PLACE ground station on a 600-b/s digital-data link.

Having thus available specific values of R_1 , R_2 and R_3 for a given mobile user, the PLACE system computes (in real time) two independent line-of-positions* (LOP 1 and LOP 2, Fig. 2) for that user; two possible positions are determined - the actual position, P_1 , and an ambiguous position, P_2 , the latter being resolved by a priori information.

Communication-satellite C-band frequencies at 4 GHz (downlink) and 6 GHz (up-link) were employed in all rf links for the Sea Tests in the Vanguard/PLACE Experiment (Fig. 3). The ranges R_1 and R_2 were computed directly from sidetone-ranging

*An LOP is generated by a range measurement from one satellite to a user (e.g., R_1), and range to geocenter, R_3 .

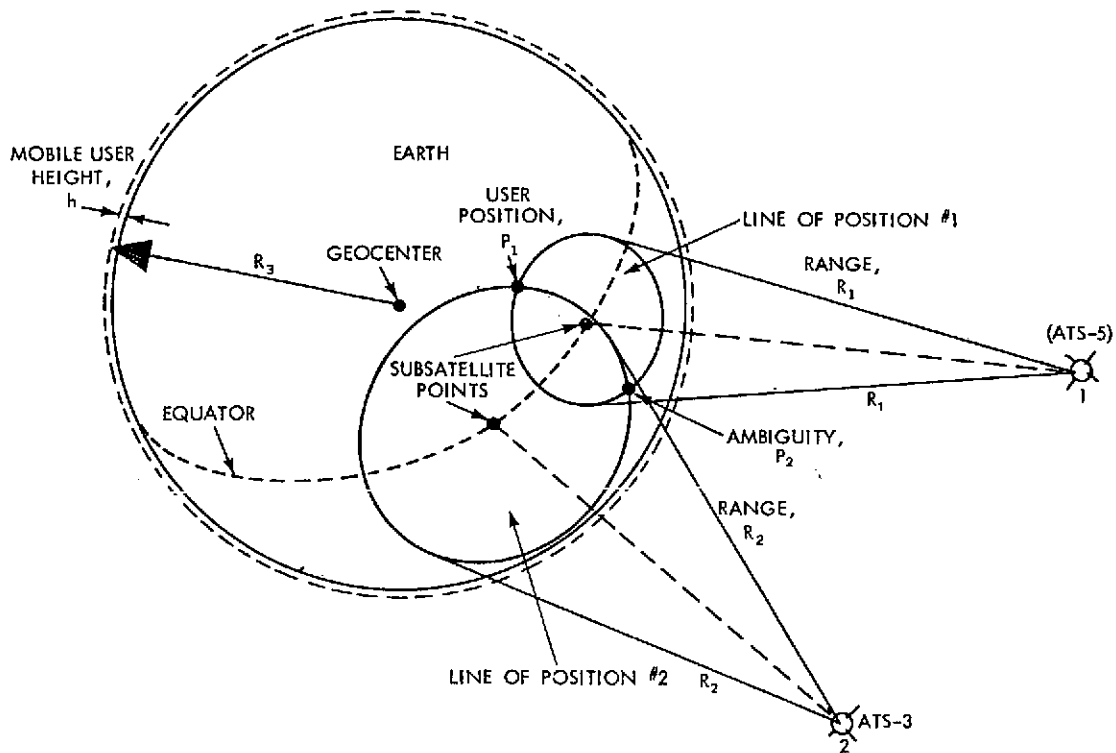


Fig. 2. Mobile User Position Fixing by Direct 2-Way Ranging to Two Synchronous Spacecraft

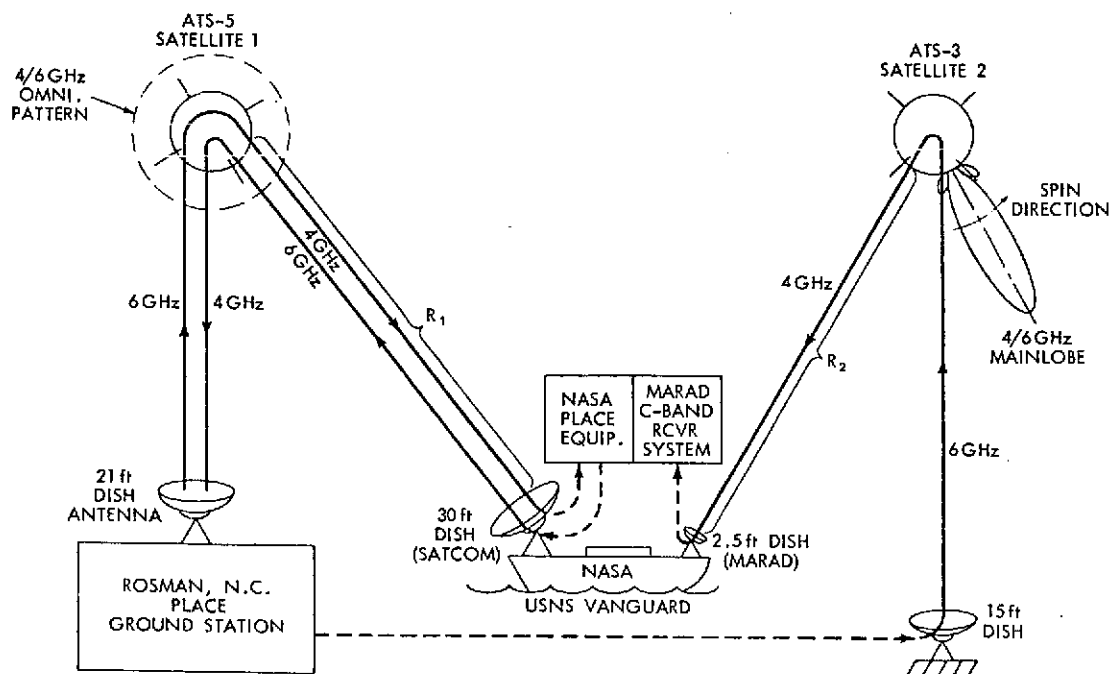


Fig. 3. Vanguard/PLACE Experiment at C-Band

measurements for the 2-way, C-band links between the Rosman station and the Vanguard. R_1 is derived from 2-way, sidetone-ranging measurements between the Rosman station, the ATS-5 satellite and the Vanguard; whereas the range R_2 is derived from sidetone-ranging measurements made between the Rosman station, ATS-3 the second satellite, and the Vanguard.

The sidetone-ranging transmission from the Rosman, 21 ft-diameter, dish antenna (ATS Mobile Terminal), via ATS-5, to the Vanguard's 30 ft (SATCOM) dish antenna is continuous; however, PLACE equipment at Rosman counts time to an assigned time slot and commands NASA-PLACE equipment on the Vanguard to reply with a return ranging-signal burst at the proper time. The range R_1 is then computed for this propagation path (Fig. 3).

The sidetone-ranging transmission from the Rosman, 15 ft-diameter, dish antenna (Fig. 3) to the ATS-3 satellite is also continuous; however, the high-gain, C-band antenna on ATS-3 is spinning at approximately 97 rpm which means the mainlobe views the earth for only about 30 ms per turn. Consequently, the ATS-3 downlink signal, at 4 GHz, to the Vanguard's 2.5 ft dish antenna, appears intermittently every 0.6 s (approximate spin period), and lasts for only 30 ms. Subsequently, the NASA-PLACE equipment on the Vanguard contains digital-type, phase-lock loops which are individually locked to range tones intermittently received from ATS-3, that recover and reproduce continuous (but delayed) replicas of the range tones originating at the Rosman station.

The range tones received from the ATS-3 satellite are in turn relayed back to the Rosman station by way of the Vanguard's SATCOM terminal and the ATS-5 satellite (Fig. 3). The range R_2 is then computed for this more complex propagation path.

Various time delays in transmission cables, station electronic equipment, ATS satellite repeaters, and the propagation path introduce range biasing when determining ranges R_1 and R_2 . The biasing due to the majority of the delays are eliminated by equipment calibration. The remainder of the range biasing is negligibly small; for example, the time delay uncertainty in the ATS-3 and ATS-5 C-band repeaters is known within 50 ns (15 m, one-way range error), and the maximum, uncorrected, propagation delay in the atmosphere³ is also on the order of 50 ns at 8 GHz - both negligible compared to the PLACE basic instrumentation accuracy of 100 m rms, in range, due to internal variance.

PLACE Hardware Design. - In early 1970, a NASA hardware contract for several aircraft transponders, containing an L-band transmitter/receiver and modem, was issued;⁹ consequently, in mid-1971, a similar contract¹⁰ was awarded for PLACE ground-station equipment, for an approved PLACE Experiment on the ATS-F satellite.

In the Fall of 1972, members of the NASA-Goddard Communications and Navigation Division originated the concept of employing the Vanguard to demonstrate the PLACE system at C-band (4/6 GHz). The pending delivery of the PLACE hardware was then made commensurate with the Vanguard's departure date (March 28, 1973). However, it became necessary to fabricate an additional rack of electronic hardware, for installation on the Vanguard, over-and-above that PLACE hardware already committed for the ATS-F/PLACE Experiment.

Sidetone-ranging measurements from the Rosman station to the Vanguard, via ATS-5, are made by means of four sinusoidal tones at 8.575, 8.55, 8.40 and 7.35 kHz; a second set of range tones, consisting of only three tones at 8.575, 8.40 and 7.35 kHz, are phase modulated (1 rad rms deviation) and transmitted to the Vanguard via the ATS-3 satellite. The second set of range tones are in turn relayed back to the Rosman station by means of the Vanguard SATCOM terminal and the ATS-5 satellite (Fig. 4).

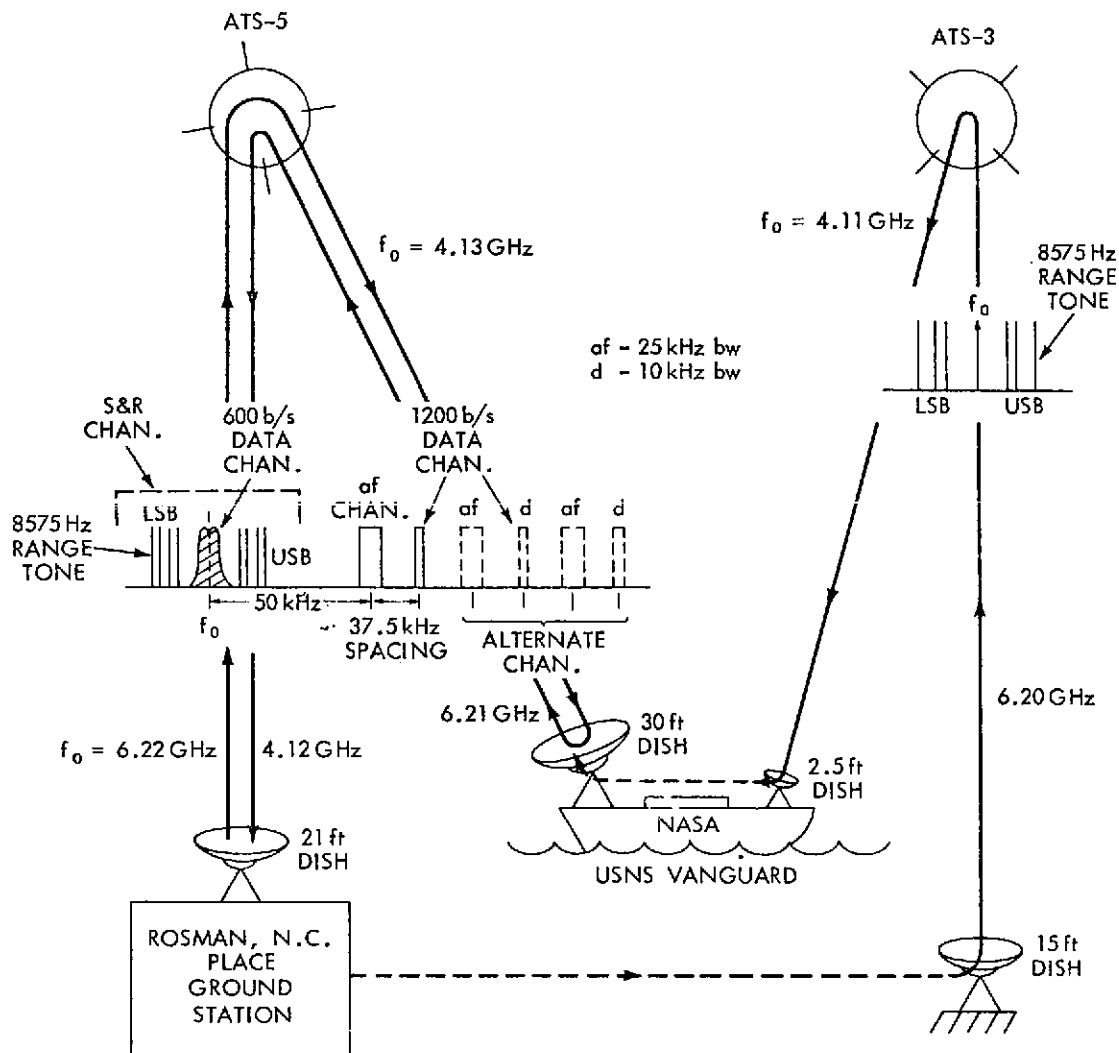


Fig. 4. Vanguard/PLACE Experiment Frequency Spectrum

The ranging replies from the Vanguard to ATS-5 consist of tone bursts that are timed, sequentially, in a time-division-multiplex (TDM) manner. The TDM sequence repeats itself each 64 s (an epoch), and contains 320 time slots, each slot length being 200 ms long. For example, the range tones from which the range R_1 is derived is contained within a single 200-ms time slot; whereas the range tone information for range R_2 is contained in an adjacent, identical, time slot.

Each 200-ms time slot constitutes a single ranging measurement that is integrated for 120 ms; ordinarily, one ranging measurement is made per epoch (64 s), representing a position-fix update rate of 1/min. However, a faster update rate is available; an update rate of 10 ranging measurements per min. was selected for the Vanguard/PLACE Experiment to demonstrate this capability and provide more ranging data. A necessary condition is that the mobile user does not move appreciably, between ranging measurements, compared to 1 nmi (the system accuracy).

Timing synchronization is established by means of a differentially-coherent, phase shift keyed (DCPSK) data transmission at 600 b/s, which together with the four range tones, constitutes the surveillance and ranging (S and R) channel (Fig. 4). The 600-b/s

digital-data signal and the four ranging tones are modulated in phase quadrature¹¹ 120 data bits/time slot (200 ms) are present in the return link for telemetry and other functions.

The PLACE frequency spectrum, for the 4 GHz and 6 GHz C-band links between Rosman, ATS-5 and the Vanguard, consists of a single S and R channel, 3 voice (af) channels, and 3 high-rate (HR) data (1200 b/s) channels (Fig. 4) that are frequency-division-multiplexed (FDM) onto separate carriers. Each mobile user is assigned one "af" channel and one "HR-data" channel, as a pair; two other such pairs are available as alternate channels for other users.

The voice (af) channels rf bandwidth is 25 kHz (± 12.5 kHz), which is more than sufficient for a voice spectrum; the voice channel employs an adaptive, narrowband, frequency-modulation (ANBFM) technique¹² whose performance has been reported by Wishna, et al.¹³⁻¹⁵

The HR, 1200-b/s, data channel also employs a differentially-coherent, phase-shift-keyed (DCPSK) modulation, similar to the 600-b/s digital data in the S and R channel, which is assigned an rf bandwidth of 10 kHz (± 5 kHz). The channel spacing between af and HR channels is front-panel adjustable as an added refinement to minimize effects of rf interference (rfi); typical channel spacings are shown in Fig. 4.

In order to further-reduce rfi, optimum values of the C-band carrier frequency, f_0 , were selected which fall within the 25-MHz rf passband of ATS-5's relay repeater (frequency translation mode).

Rosman Station Configuration.—The Vanguard/PLACE Experiment's equipment configuration for the Rosman station (Fig. 5), for the Sea Tests, contains both 6 GHz and 4 GHz links between Rosman and the ATS-3 satellite. Although not a ranging link, the fixed, 8°-wide, mainlobe beamwidth of the 2 ft-diameter dish antenna in the 4-GHz Monitor Link monitors received signal strength from ATS-3 to provide information to steer manually the narrow, 0.7°, beamwidth (3 dB) of the Rosman, 15 ft-diameter, transmitting dish antenna. This insures that the 0.7° beam is always pointing toward ATS-3; the ATS-3 satellite drifts approximately $\pm 3^\circ$ in latitude, about the equator, over a 24-h period. Because of satellite local-oscillator frequency drifts, a secondary function of the Monitor Link is to provide a vernier frequency

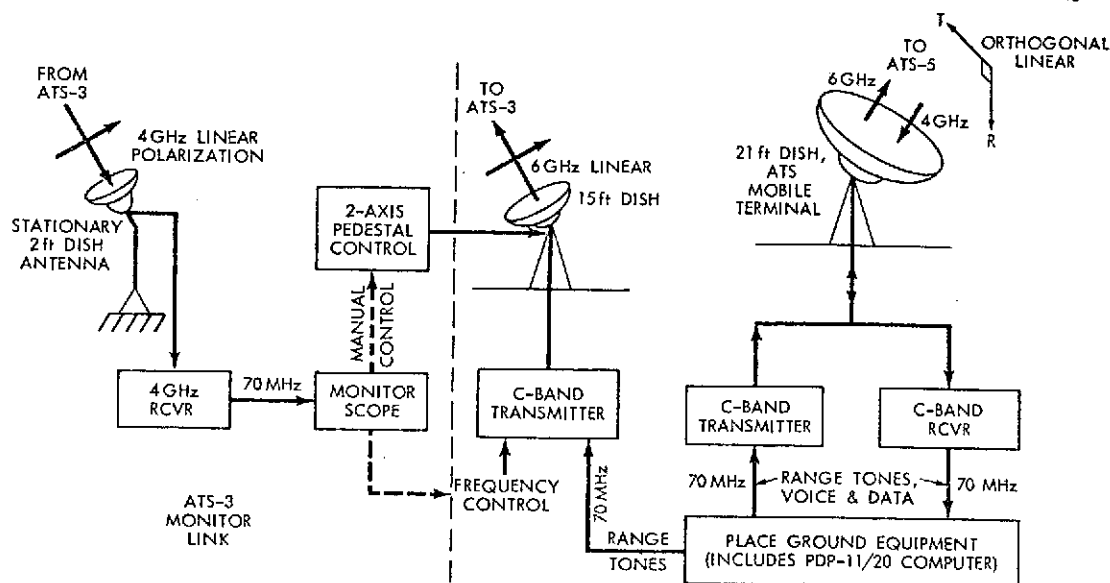


Fig. 5. Rosman Station Configuration, Vanguard/PLACE Experiment Sea Tests

adjustment to maintain a constant frequency of 4.1100 GHz (f_0), from ATS-3 to the Vanguard, by manually controlling the uplink frequency at the Rosman C-band transmitter (Fig. 5). The ATS-3 Monitor Link is not required in an operational system.

The PLACE Control Center (Fig. 5) contains an on line type PDP-11/20 computer, including a Central-Processor Unit (CPU), DEC writer, Master and Slave Tape Units, and 132-column-wide Line Printer, for calculating in real time the latitude/longitude position coordinates of the Vanguard, using a Kalman-type filter. A priori, predicted, satellite-ephemeris data, for both the ATS-3 and ATS-5 satellites, is inputted to the PDP-11/20 computer from a magnetic tape whose source data originated from the NASA-Goddard Range and Range Rate (RARR) system.¹⁶ An updated position of the Vanguard can be computed off line from recordings of ranging measurements from the PDP-11/20 Tape Units, at a time when updated, and more accurate, post-measurement RARR data becomes available.

The PLACE Ground Equipment at Rosman (Fig. 5) originates 2-way, sidetone-ranging signals, 2-way voice communications, and 2-way, HR-data (1200b/s) communications, for transmission to-and-from the Vanguard's SATCOM Terminal, via the ATS-5 satellite. Interfacing with the ATS Mobile Terminal occurs at 70-MHz i-f; C-band transmissions to-and-from ATS-5 have orthogonal-linear polarization.

The PLACE Ground Equipment also originates the second set of 3 range tones for transmission to the Vanguard via the 15 ft dish antenna, and the ATS-3 satellite. Interfacing with C-band transmitter is also at 70MHz; C-band transmissions to ATS-3 are linearly polarized and have a fixed, polarization-tilt angle.

Instrumentation included with the PLACE Ground Equipment, at Rosman, consist of an af tape recorder, and a Frederick-600 Data Test Set for maintaining 2-way voice (af) and 1200-b/s HR, digital-data communications, respectively, with similar equipments located on board the Vanguard. A 7-channel, instrumentation recorder (type FR-600) was located at Rosman, and onboard the Vanguard, for recording functions including receiver age, GMT time-code signals, and bit error probability in the 1200b/s data channel.

Vanguard Equipment Configuration, Sea Tests. -C-band equipment on board the Vanguard maintains communications with both the ATS-3 and ATS-5 satellites for the Sea Tests (Fig. 6). The SATCOM's, 30 ft-diameter, C-band, dish antenna receives 4 GHz transmissions from ATS-5 including the S and R channel (4 range tones and 600b/s data), voice and 1200-b/s (HR) data signals, originating within PLACE Ground Equipment at the Rosman station.

A critical subsystem is the PLACE Aircraft Modem which relays the S and R channel, containing the 4 range tones, back to Rosman via the SATCOM's C-band transmitter and the ATS-5 satellite. A 60/70MHz i-f Converter translates the 60 MHz i-f output from the modem up to 70MHz required for the SATCOM system. The modem also receives, and originates, both voice (af) and 1200b/s digital-data signals.

ATS-3, the second satellite, relays the second set of 3 range tones also originating at Rosman, to the Vanguard by means of a 2.5ft-diameter, C-band, dish antenna system onboard the Vanguard.

C-band Link Calculations. -For a transmitting and receiving antenna axially aligned within the far field, the power at the receiving antenna's output terminals is given by

$$P_R = (P_T G_T) G_R \left[\frac{\lambda}{4\pi d} \right]^2 \text{ watt} \quad (1)$$

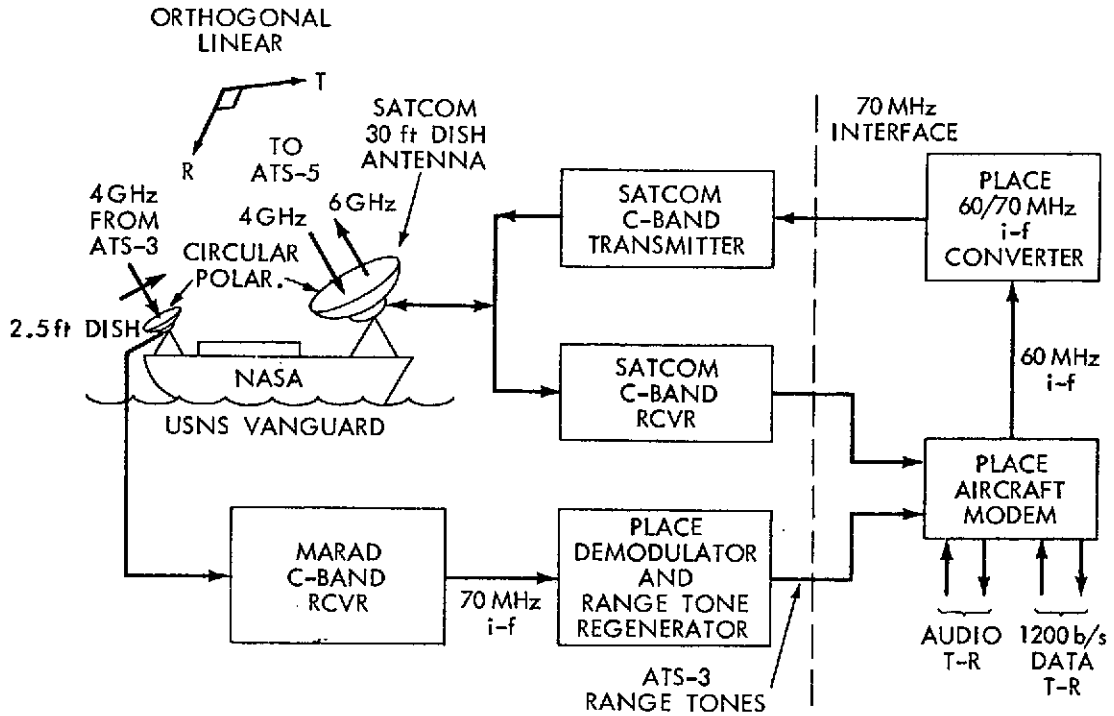


Fig. 6. Vanguard/PLACE Experiment Equipment on Vanguard for Sea Tests

- P_T = input power to transmitting antenna, watts
 G_T = effective power gain of transmitting antenna
 $(P_T G_T)$ = effective radiated power (ERP) of transmitting antenna, watts
 G_R = effective power gain of receiving antenna
 λ = free space wavelength
 d = distance between antennas (same units as λ)
 $\left[\frac{\lambda}{4\pi d} \right]^2$ = free space path loss factor where space loss,

$$A_L = 20 \log \left[\frac{\lambda}{4\pi d} \right] \text{ dB} \quad (2)$$

It is helpful to express (1) in decibels referred to 1 watt as

$$\text{dBW} = 10 \log P_R \quad (3)$$

In general, a low-noise preamplifier is located at the receiving antenna's output terminals to reduce the system effective noise temperature defined by Kraus¹⁷ as

$$T_{\text{sys}} = T_R + \epsilon T_A + (1-\epsilon) T_0 \text{ degrees Kelvin, } ^\circ\text{K} \quad (4)$$

where

T_R = preamplifier noise temperature, $^\circ\text{K}$, including contributions from following stages.

The second and third terms on the right-hand side of (4) result when transmission line loss between the antenna and preamplifier input terminals is not zero, but

$\epsilon \leq 1$, the transmission line power loss,

T_A = antenna noise temperature, $^\circ\text{K}$, and

T_0 = ambient physical temperature of transmission line, $^\circ\text{K}$.

The received signal-to-noise power density can then be defined as

$$\frac{P_R}{N_0} = \frac{P_R}{k T_{sys}} \text{ dB-Hz} \quad (5)$$

where

N_0 = system noise power density, dBW/Hz, and

k = Boltzmann's constant = $1.38 \times 10^{-23} \text{ J/}^\circ\text{K}$.

The 4/6 GHz C-band links between the Rosman station and the Vanguard have a satisfactory signal-to-noise power density even when ATS-5's omnidirectional antenna (Fig. 7) is employed. An analysis of the 2-way RF links through ATS-5, using (1)-(5), is given in Tables I and II.

When utilizing ATS-5's omnidirectional C-band antenna, reliable 2-way communications between Rosman and the Vanguard can be established only when using

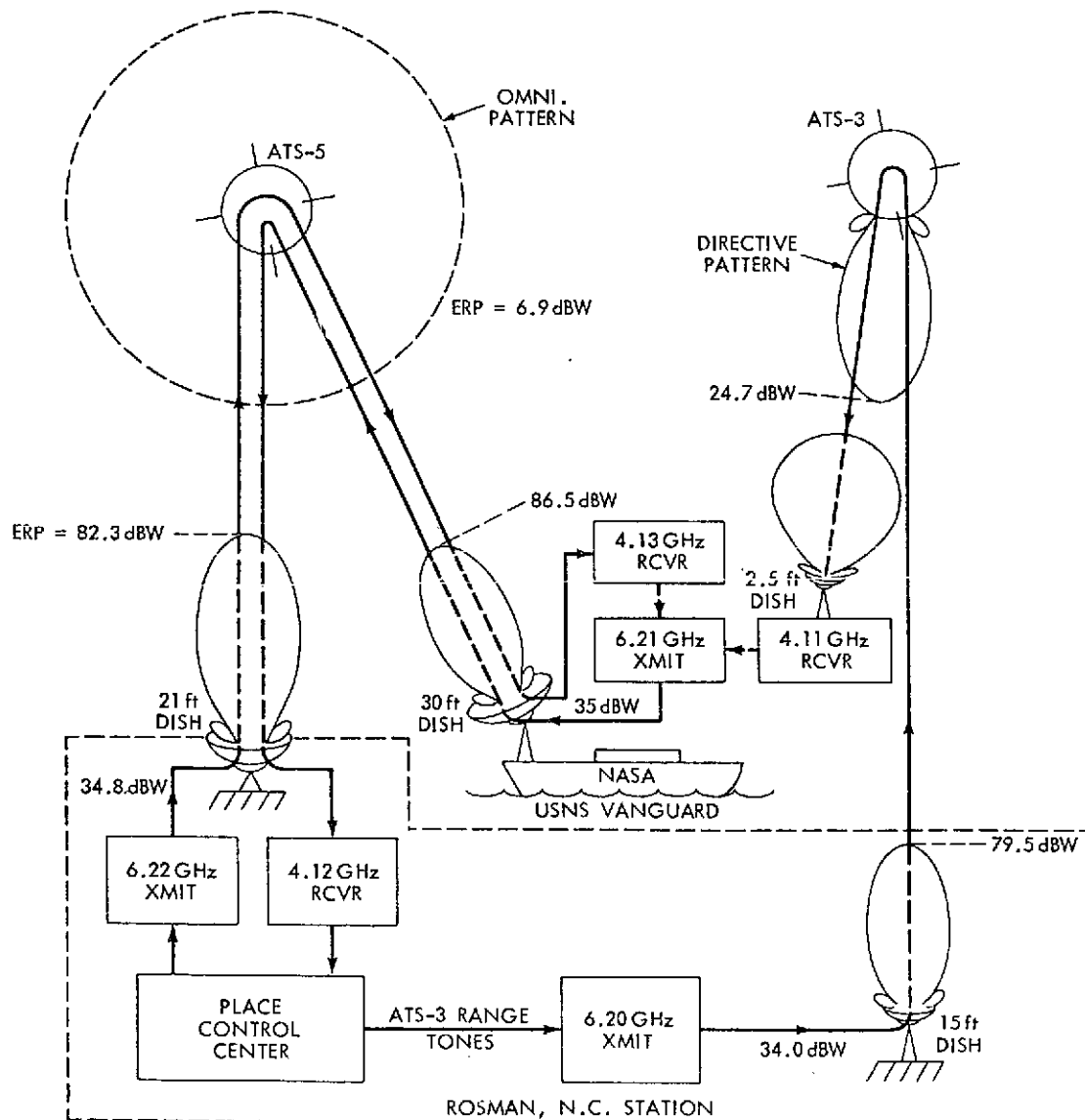


Fig. 7. Vanguard/PLACE Experiment C-band Link Parameters

kw-power transmitters, in the uplinks, and low-noise preamplifiers in RF link receivers. For example, the 6.22 GHz, shore-to-ship uplink from Rosman to ATS-5 employs a 3kw (34.8 dBW) transmitter, into a 21 ft-diameter dish antenna with 48.5 dB gain, resulting in a linearly-polarized ERP of 82.3 dBW (Table I). From (1)-(3), the signal power out of ATS-5's co-polarized receiving antenna becomes

$$P_R = (P_T G_T) G_R \left[\frac{\lambda}{4\pi d} \right]^2$$

$$\begin{aligned} P_T G_T &= 34.8 \text{ dBW} + 48.5 \text{ dB} - 1.0 \text{ dB (loss)} \\ &= 82.3 \text{ dBW (ERP)} \end{aligned}$$

$$G_R = 1.3 \text{ dB}^* - 0.4 \text{ dB (loss)} = 0.9 \text{ dB}$$

$$\lambda = 4.82 \text{ cm @ } 6.22 \text{ GHz}$$

$$d = 37,700 \text{ km } (3.77 \times 10^9 \text{ cm}) \text{ nominal slant range from Rosman to ATS-5 @ } 105^\circ \text{ W longitude}$$

$$\begin{aligned} A_L &= 20 \log \left[\frac{\lambda}{4\pi d} \right] \\ &= 20 \log \left[\frac{4.82 \text{ cm}}{4\pi (3.77 \times 10^9 \text{ cm})} \right] = -199.9 \text{ dB} \end{aligned}$$

$$\begin{aligned} P_R &= \underbrace{82.3 \text{ dBW}}_{\text{ERP}} + \underbrace{0.9 \text{ dB}}_{G_R} - \underbrace{199.9 \text{ dB}}_{A_L} - \underbrace{1.7 \text{ dB}}_{\text{Propagation losses}} \\ &= -118.4 \text{ dBW.} \end{aligned}$$

From (4), (5) for ATS-5's C-band receiver and omnidirectional antenna,

$$\begin{aligned} T_{\text{sys}} &= T_R + \epsilon T_A + (1-\epsilon) T_0 \text{ } ^\circ\text{K} \\ &= 893^\circ + 0.912 (290^\circ) + (1-0.912) 290^\circ \\ &= 1183^\circ\text{K} \end{aligned}$$

$$\begin{aligned} N_0 &= k T_{\text{sys}} = (1.38 \times 10^{-23} \text{ J/}^\circ\text{K}) 1183^\circ \\ &= 1.64 \times 10^{-20} \text{ W/Hz} = -197.9 \text{ dBW/Hz} \end{aligned}$$

$$\begin{aligned} \frac{P_R}{N_0} &= -118.4 \text{ dBW} - \left(-197.9 \frac{\text{dBW}}{\text{Hz}} \right) \\ &= 79.5 \text{ dB-Hz.} \end{aligned}$$

Similarly, the 4.13 GHz downlink signal from ATS-5 to the Vanguard's SATCOM antenna (30 ft diameter dish) has an ERP of 6.9 dBW (Table I) which is received by the SATCOM 30 ft dish, having 48.0 dB gain, and a 70°K, low-noise (cooled), parametric preamplifier. The resulting signal-to-noise power density out of the SATCOM receiving system (Fig. 6) is $P_R/N_0 = 58.0 \text{ dB-Hz}$ (Table I) into the PLACE Aircraft Modem onboard the Vanguard. This value is 4 dB greater than the minimum required.

The minimum value of P_R/N_0 is 54 dB-Hz, a value required for a fully-loaded PLACE spectrum consisting of S and R channel (600 b/s data and 4 range tones), 3 voice channels and 3 H-R (1200 b/s) data channels using ATS-5's frequency-translation

*ATS-5's omnidirectional, linearly polarized, radiation is actually a dipole-shaped pattern with nulls roughly perpendicular to the earth-satellite line.

(FT) mode.¹⁰ At the minimum value, threshold values for individual channels in the composite PLACE spectrum become:

S and R	42 dB-Hz
H-R (1200 b/s) Data	42 dB-Hz
Voice	46 dB-Hz.

Similarly, the return, ship-to-shore, RF link from the Vanguard's SATCOM system to Rosman's 21 ft-dish, ATS Mobile Terminal produces a comparable value of $P_R/N_0 = 57.0$ dB-Hz (Table II).

Whereas the 2-way, C-band links between Rosman and the Vanguard (via ATS-5) produce sidetone-ranging measurements from which the satellite-to-user range, R_1 , is derived, a 1-way C-band link from Rosman to the Vanguard (via ATS-3) produces sidetone-ranging measurements from which the second satellite-to-user range, R_2 , is obtained. The 6.20 GHz, shore-to-ship, uplink from Rosman to ATS-3 employs a 2.5 kw (34.0 dBW) transmitter, into a 15 ft-diameter dish antenna with 46.0 dB gain (Fig. 7), resulting in a linearly-polarized ERP of 79.5 dBW (Table III). Since ATS-3 has a co-polarized, directional, C-band receiving antenna (16.2 dB gain), a peak value of $P_R/N_0 = 91.5$ dB-Hz exists in ATS-3's receiver when the peak of ATS-3's main lobe sweeps past Rosman.

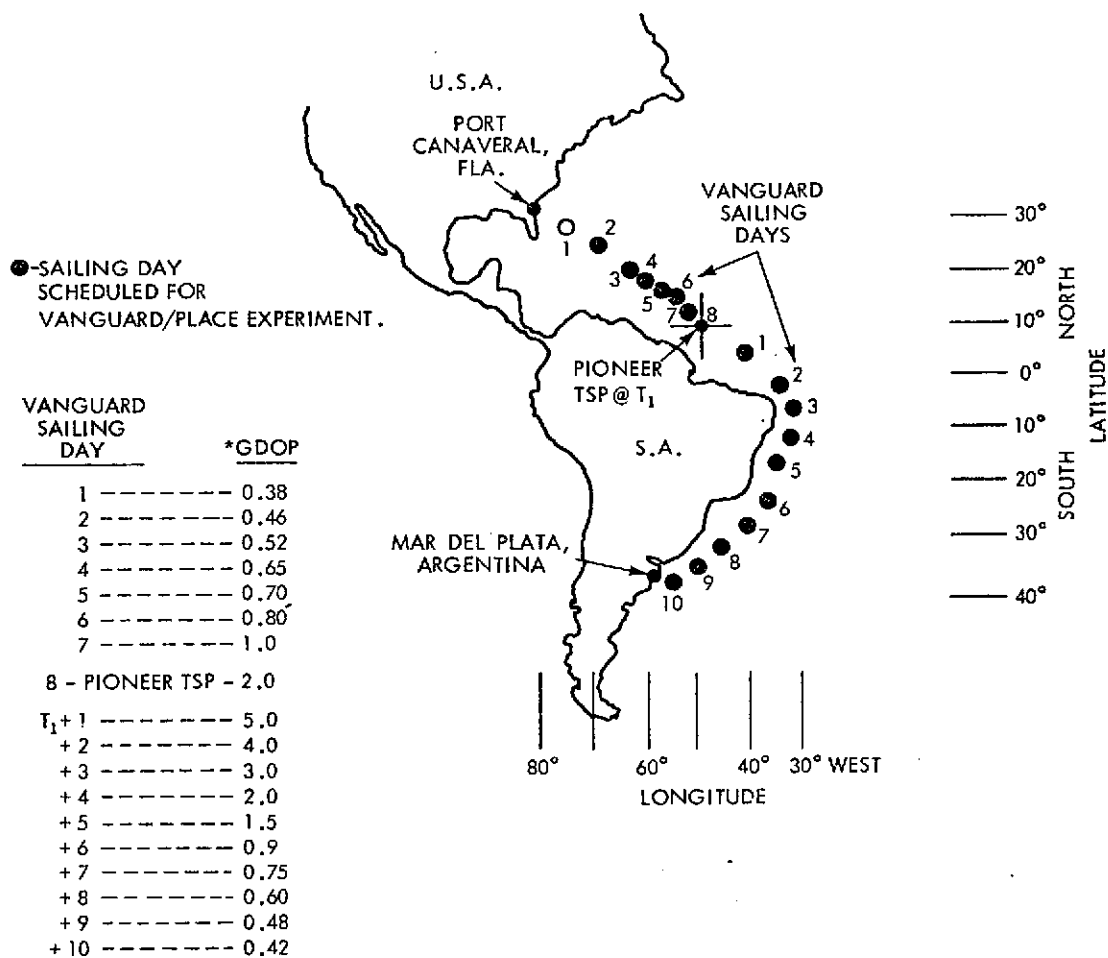
Similarly, on the downlink, a peak value of $P_R/N_0 = 53.6$ dB-Hz exists in the MARAD C-band receiving system, utilizing a 2.5 ft-diameter dish (27.3 dB gain) and a 200°K, low-noise preamplifier,² onboard the Vanguard. This value exceeds the signal threshold of the onboard, digital, phase-lock loops by a sufficient margin so that the electrical phase error of the range tones does not exceed 1/3° rms, a negligible error, between signal peaks.

Operational Test Plan.—Operational checkout testing between the Rosman and Vanguard terminals, using ATS-5, began on March 5, 1973; the Sea Tests using both ATS-3 and ATS-5, were made during the 8 days when the Vanguard sailed from Port Canaveral to the PIONEER Test Support Position (TSP), followed by an additional 10 days while the Vanguard sailed to Mar del Plata, Argentina (Fig. 8).

The Vanguard's route over both northerly and southerly latitudes provided an excellent opportunity to measure geometrical dilution of position (GDOP). GDOP values in Figure 8 give ship position-location error when multiplied by satellite position error (one standard deviation), assumed equal and independent in any direction for both satellites. Theoretical values of GDOP range from about 0.4 to 5.0 for the Vanguard's sea route, for ATS-3 and ATS-5 located at 73°W and 105°W longitude, respectively (Fig. 8).

Approximately 60 hours of experiment time were scheduled for position-location measurements, involving both the ATS-3 and ATS-5 satellites, during the 18 days the Vanguard was sailing. The Vanguard/PLACE Sea-Test experiment began March 29, 1973, the second day out of port (Fig. 8), and extended through April 15th while the Vanguard travelled from Port Canaveral to the alternate port of Buenos Aires, Argentina. Approximately 50 hours of position-location measurements were actually obtained, during the Sea Tests, and 30-odd hours of voice and H-R (1200 b/s) data transmissions were recorded.

Preliminary Test Results.—The Vanguard/PLACE experiment, during the Sea Tests, was an overwhelming success in that the principal objectives of the experiment were met. Initial quick-look results indicate that the Vanguard's position was determined within two nautical miles, even for uncorrected data, compared to the Vanguard's true position. For example, typical PLACE-computed data (Fig. 9)



*GDOP - GEOMETRICAL DILUTION OF POSITION
**TSP - TEST SUPPORT POSITION FOR PIONEER 11 LAUNCH.

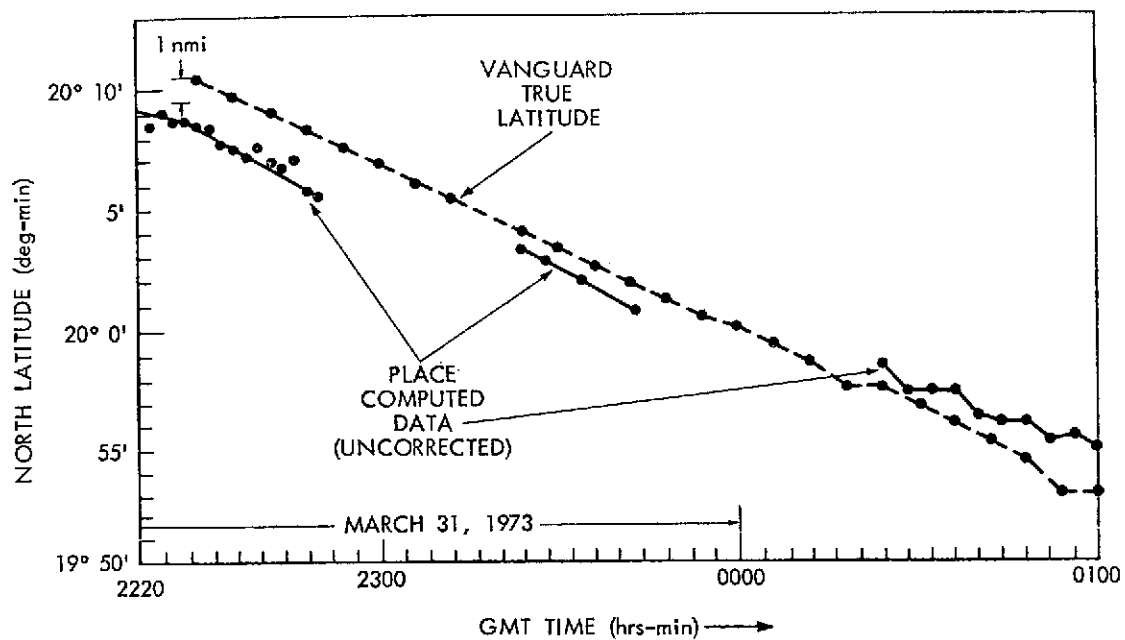
Fig. 8. Vanguard Sea Route for PLACE Experiment

demonstrates that the Vanguard's north latitude was determined within 2 nmi and west longitude within 1 nmi, for 1.5 hrs of data. The corresponding theoretical GDOP value is about 0.6 for this location (Fig. 8). Updated, post-measurement, satellite-ephemeris data should improve the test result.

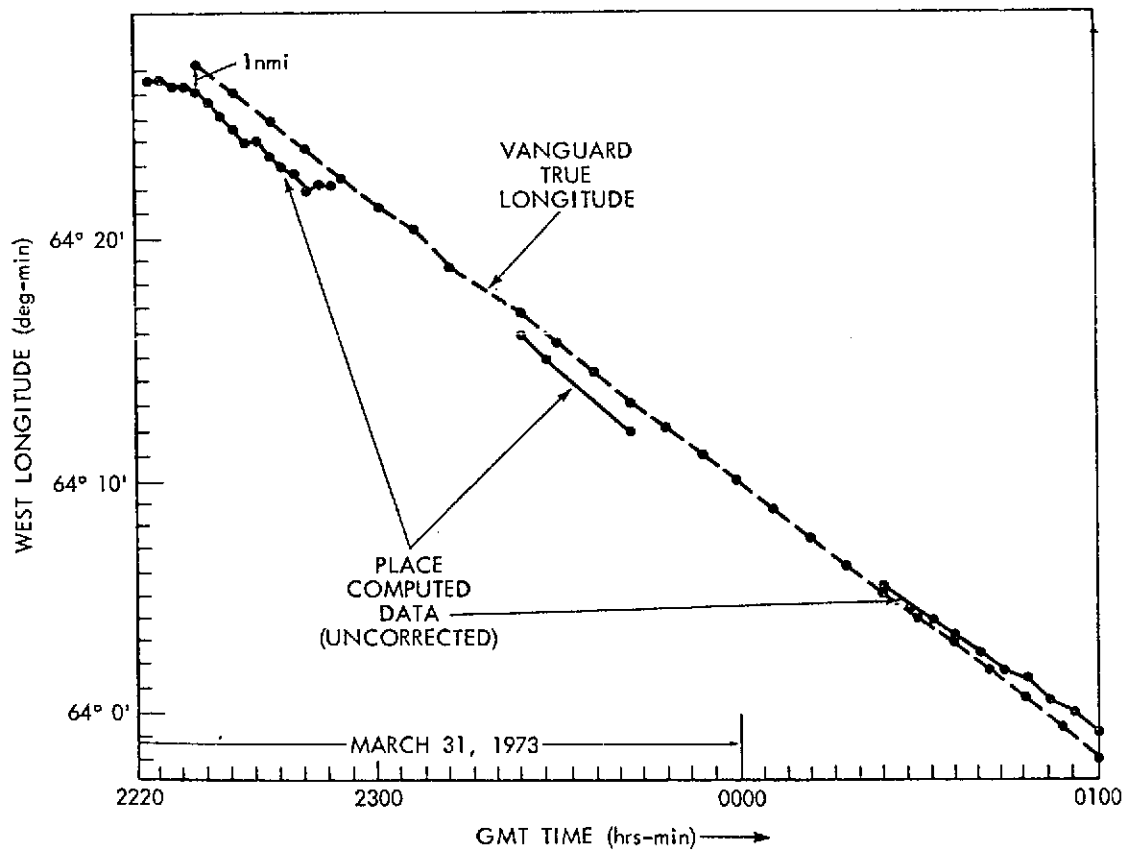
As stated earlier, the Vanguard's true latitude and longitude coordinates are known within ± 0.1 nmi by means of onboard navigation instrumentation. The true position reported by the Vanguard is a composite average of data from various systems including the ship's inertial navigation system (SINS), and position-fixes from the SRN-9, transit-satellite system.

A preliminary analysis of the 2-way voice channel measurements indicate that the performance of the ANBFM voice system was excellent as determined by intelligibility and articulation-index analysis tests. However, a sharp null in the scalloped, omnidirectional, antenna radiation pattern, in the ATS-5 satellite, caused some difficulty with synchronization in the digital-data communications channels.

ATS-5 Trilateration Tests. -To determine the satellite-to-user ranges R_1 and R_2 (Fig. 2) requires a knowledge of the satellite-to-ground station range, the latter range being provided either by a priori satellite-ephemeris predictions, or in situ,



(a) Vanguard North Latitude



(b) Vanguard West Longitude

Fig. 9. Experimental Position-Location Data, Vanguard/PLACE Sea Test

satellite-trilateration measurements. Trilateration is the preferred method since more frequent, and more accurate, updates of satellite position can be provided.

The unique location of the Vanguard, while docked at Mar del Plata, Argentina, provides unusually long baselines with the Rosman, N.C. and Mojave, California NASA-STDN stations for accurately determining the position of the ATS-5 satellite by geometrical-trilateration measurements. To accomplish this, a relay transponder will be placed at each of the three stations, whose locations must be known within 15 m, and performing sidetone-ranging measurements with the PLACE ground equipment at Rosman.

Ideally, the orbital position of the satellite should be known within 1.5 km^1 for determining a user's position location within 1 nmi. The objective of this portion of the experiment is to locate the ATS-5 satellite's position with this accuracy, independently of external data defining satellite orbital motion (i.e., orbital elements).

Satellite trilateration at C-band (4/6 GHz) provides rf links essentially free of propagation anomalies;³ however, in the forthcoming ATS-F PLACE Experiment⁵⁻⁸ trilateration tests will be performed using a combination of C-band and aeronautical L-band frequencies. Therefore, it would be desirable to make simultaneous C-band and L-band trilateration measurements, using ATS-5, to compare their relative performance.

At the suggestion of Anderson^{18,19} the General Electric Company's (GE) Radio-Optical Observatory, located at Schenectady, N.Y., will conduct 2-way sidetone-ranging measurements, at L-band, simultaneously with NASA-Vanguard/PLACE sidetone-ranging measurements, at C-band, for satellite trilateration. Such a joint experiment will provide a direct comparison of C-band and L-band performance.

The ATS-5 satellite contains both C-band and L-band relay repeaters which may be operated, simultaneously; Kissel^{20,21} describes the performance characteristics of the ATS-5 satellite.

Conclusions.—The system design, and an experiment operational test plan, have been described for demonstrating and evaluating the NASA-Goddard Position Location and Aircraft Communications Equipment (PLACE), at C-band, using NASA's ship, the USNS Vanguard, and the ATS-3 and ATS-5 synchronous satellites.

The Sea Test phase, extending from March 29, 1973 to April 15, 1973, has been successfully completed. Approximately 50 hrs of position-location measurements were obtained, and 30-odd hours of voice and H-R (1200 b/s) digital-data transmissions were recorded.

The principal objectives of the experiment were achieved; typical PLACE-computed, position-location data is shown for the Vanguard.

The test data and practical operational experience gained from this experiment firmly establish that the PLACE technical concept is valid for mobile-user surveillance and communications. The PLACE concept will be evaluated further at L-band, in forthcoming tests with the Application Technology Satellite ATS-F, scheduled for launch in early 1974.

The joint NASA/GE, C-band/L-band, satellite-trilateration tests began on May 3, 1973, with the ATS-5 satellite, and will be continued for several months.

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Table I

ATS-5 RF Link Calculation, Shore-to-Ship

Parameters	Rosman to ATS-5 to Vanguard	
	6.22 GHz Uplink	4.13 GHz Downlink
Transmit antenna gain (dB)	48.5	1.3
Transmit network loss (dB)	-1.0	-0.4
Transmitter power out (dBW)	34.8	6.0*
ERP (dBW)	82.3	6.9
Receive antenna gain (dB)	1.3	48.0
Receive network loss (dB)	-0.4	-0.2
Free space loss, A_L (dB)	-199.9	-196.3
Atmospheric loss (dB)	-0.2	-0.2
Polarization loss (dB)	-0.8	-3.8**
Antenna pointing loss (dB)	-0.7	-1.5
Net propagation loss (dB)	-201.6	-201.8
ATS-5 repeater loss (dB)	—	-3.5
Total received signal power, P_R (dBW)	-118.4	-150.6
System effective noise temperature, T_{sys} (°K) @ $T_0 = 290^\circ\text{K}$	1183°	100°
Antenna noise temperature, T_A (°K)	290°	25°
Noise power density, N_0 $\frac{\text{dBW}}{\text{Hz}}$	-197.9	-208.6
Signal-to-noise power density, P_R/N_0 (dB-Hz)	79.5	58.0

*2 TWT's on ATS-5 have a total output power, $P_T = 8\text{ W}$ (9.0 dBW); assume 2 equal-level input signals which equally power-share the repeater output power.

**Linear polarization transmit and circular polarization receive.

Table II
ATS-5 RF Link Calculation, Ship-to-Shore

Parameters	Vanguard to ATS-5 to Rosman	
	6.21 GHz Uplink	4.12 GHz Downlink
Transmit antenna gain (dB)	52.0	1.3
Transmit network loss (dB)	-0.5	-0.4
Transmitter power out (dBW)	35.0	6.0*
ERP (dBW)	36.5	6.9
Receive antenna gain (dB)	1.3	45.0
Receive network loss (dB)	-0.4	-0.4
Free space loss, A_L (dB)	-199.9	-196.3
Atmospheric loss (dB)	-0.2	-0.2
Polarization loss (dB)	-3.8**	-0.8***
Antenna pointing loss (dB)	-0.7	-1.5
Net propagation loss (dB)	-204.6	-198.8
ATS-5 repeater loss (dB)	—	-3.0
Total received signal power, P_R (dBW)	-117.2	-150.3
System effective noise temperature, T_{sys} (°K) @ $T_0 = 290^\circ\text{K}$	1183°	135°
Antenna noise temperature, T_A (°K)	290°	35°
Noise power density, N_0 $\frac{\text{dBW}}{\text{Hz}}$	-197.9	-207.3
Signal-to-noise power density, P_R/N_0 (dB-Hz)	80.7	57.0

*2 TWT's on ATS-5 have a total output power, $P_T = 8\text{W}$ (9.0 dBW); assume 2 equal-level input signals which equally power-share the repeater output power.

**Circular polarization transmit and linear polarization receive.

***Co-polarized transmit and receive linear polarizations.

Table III

ATS-3 RF Link Calculation, Shore-to-Ship

Parameters	Rosman to ATS-3 to Vanguard	
	6.20 GHz Uplink	4.11 GHz Downlink
Transmit antenna gain (dB)	46.0	16.2
Transmit network loss (dB)	-0.5	-0.5
Transmitter power out (dBW)	34.0	9.0
ERP (dBW)	79.5	24.7
Receive antenna gain (dB)	16.2	27.3
Receive network loss (dB)	-0.4	-1.0
Free space loss, A_L (dB)	-200.0	-196.5
Atmospheric loss (dB)	-0.2	-0.2
Polarization loss (dB)	-0.8	-3.0*
Antenna pointing loss (dB)	-0.7	-1.5
Net propagation loss (dB)	-201.7	-201.2
ATS-3 repeater loss (dB)	—	0
Total received signal power, P_R (dBW)	-106.4	-150.2
System effective noise temperature, T_{sys} (°K) @ $T_0 = 290^\circ\text{K}$	1183°	300°
Antenna noise temperature, T_A (°K)	290°	50°
Noise power density, N_0 $\left(\frac{\text{dBW}}{\text{Hz}}\right)$	-197.9	-203.8
Signal-to-noise power density, P_R/N_0 (dB-Hz)	91.5	53.6

*Linear polarization transmit and circular polarization receive.